FREQUENCY TRANSFER USING GPS CODES AND PHASES: SHORT- AND LONG-TERM STABILITY

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Abstract

GPS codes and carrier phases measured by multi-channel geodetic receivers can be used for accurate frequency-transfer applications when using geodetic data analysis methods.

At the Royal Observatory of Belgium, previous on-site studies have shown the sensibility of the frequency transfer to the temperature variations around the hardware (GPS receiver, cable, and antenna). Now, some parts of the old setup have been improved: the GPS receiver was moved to an environmentally controlled chamber where temperature variations are kept smaller than 0.2°C, and the old antenna cable has been replaced by a new cable with a low electrical length change versus temperature. We demonstrate that this upgrade improves the stability of the frequency transfer, especially for sub-daily averaging times. Stabilities of 1.5 to 3.10^{-15} can be routinely obtained for averaging durations of only 4 hours.

Characteristic for the geodetic analysis method is the simultaneous estimation of site positions, troposphere corrections, and other parameters, based on daily data sets. Basic observables for our computations are the (multi-satellite) common-view ionospheric-free codes and carrier phases. This daily estimation process, in addition to the presence of multipath in the code observations, introduces jumps in the estimated clock differences, which can grow up to a few ns. We focus on the minimization of the jumps between successive days to improve the long-term stability of the frequency transfer. This is possible by using overlapping data files and by carefully modeling all parameters at the day boundaries. Using IGS tracking stations, separated by 280 km, and driven by an H-maser, the results demonstrate frequency stabilities of 1.10^{-15} for averaging durations of 32 hours.

INTRODUCTION

The Royal Observatory of Belgium (ROB) started to study the use of multi-channel geodetic GPS receivers for frequency-transfer applications in 1998 [1], [2], and [3]. These receivers acquire phase and code observations from all satellites in view, and at both L_1 and L_2 frequencies.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **Frequency Transfer Using GPS Codes and Phases: Short- and Long-Term Stability**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Royal Observatory of Belgium,Avenue Circulaire 3,B-1180 Brussels, Belgium,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001481. 31st Annual Precise Time and Time Interval (PTTI) Planning Meeting, 7-9 December 1999, Dana Point, CA

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

We evaluated the critical aspects of the setup of the IGS receiver BRUS, located at the ROB, driven by a hydrogen maser, to contribute to the BIPM/IGS Pilot Project [6]. This receiver is a Rogue SNR-12 (Allen Osborne Associates), connected through a 60-m long RG-223 cable to a Dorne Margolin T antenna.

The frequency stability we obtained for the frequency transfer over a zero baseline using the carrier phases differed from 4.10^{-15} to 1.10^{-16}, for averaging times of 8 hours, mainly depending on temperature variations in the laboratory where the instruments were located [3]. We derived temperature coefficients for some of the hardware components: for the L_1 carrier-phase signal path, the response of the receiver hardware was about 30 ps/°C (Rogue SNR-12 receiver); the response of the amplifier of the H-Maser frequency was about 0.5 ns/°C.
Frequency transfer tests on a regional scale, between two IGS stations Brussels and Wettzell (640 km) both driven by a H-maser, showed that the frequency stabilities could vary between 1.10^{-14} and 2.10^{-15} (for averaging times of 4 hours). In stable laboratory temperature conditions, the main parameter now was the proper modeling of the tropospheric refraction.

The problem to evaluate the obtained frequency stabilities are the daily discontinuities, which have been reported by several authors [4], [5]. The discontinuities are due to the fact that the data analysis is usually done on blocks of daily RINEX files. Consequently, there is a jump in the obtained clock differences each day at midnight, when a new data file is started.
This is the reason why, up to now, we restricted ourselves to analyze the frequency stability obtained after only one day (the short-term stability). In this paper we will use overlapping data files to overcome this problem. In addition to this, we will compare our results to the ones obtained from another geodetic positioning technique based on undifferenced data.

NEW SETUP

It was very clear from previous work that the frequency stabilities at BRUS could be largely improved if the temperature effects on the instruments were suppressed, i.e. if the instruments were all located in temperature-stabilized rooms.
Therefore, some parts of the old setup of the BRUS station have recently been improved. The cross-correlating GPS receiver was upgraded with the ACT tracking algorithm to provide a better tracking at lower elevations and obtain direct measurements of P_1 and P_2 without the use of the Y-codes.

The upgraded receiver and the amplifier were moved to an environmentally controlled chamber, where temperature variations are kept smaller than 0.2° C. The old antenna cable was replaced by a 85-m heliax LDF2-50A cable from Andrew Cooperation. This new cable has a loss of 1.05DB per 30 m and a low electrical length change versus temperature.
The GPS antenna, a Dorne Margolin T, was not replaced and still contributes to the error budget caused by the temperature variations.

All tests have been done with respect to the IGS station in Westerbork (the Netherlands) at a distance of about 280 km from Brussels. This station has been chosen because it is also equipped with an Rogue SNR-12 receiver and driven by an H-maser. All instruments are located in a laboratory where daily temperature variations are kept within ± 0.5° C.

THE APPROACH USED

The GPS code and carrier phase data analyses were done with the Bernese 4.2 geodetic analysis software complemented with self-developed programs. Two time- and frequency-transfer approaches have been compared:

1. Using undifferenced data (based on the single-point positioning methods) and using the time-and frequency-transfer module of the Bernese 4.2 [8].
   In this case, we solve for all clocks (satellite and receiver), except one reference clock, which was chosen as the H-maser clock of the station at Brussels.
2. Using single-difference data [2], but based on the double-differencing (between a pair of stations and a pair of satellites) approach of the Bernese [7].

The advantage of using double-differenced carrier-phase data is that common error sources are reduced (troposphere, ionosphere, orbits) or even removed (station and satellite clocks) so that the data cleaning is much easier than in the case of undifferenced data. After the data cleaning, the double differences are used for ambiguity fixing and modelling of the remaining errors (mainly troposphere). The computed models and parameters are then used as a priori information for the creation of single-difference post-fit residuals with respect to a reference satellite. The synchronization errors between the two stations are directly obtained from these post-fit single-difference residuals.
Although the carrier-phase data provide all the necessary information to perform frequency transfer, they cannot provide an absolute time comparison between the two receivers; this is due to the unknown phase ambiguity of the reference satellite. The absolute information is, therefore, extracted from the smoothed single-difference code observables. This smoothing is performed on the ionospheric-free code observables, after a troposphere model, computed from the phase observables, has been applied. A full description of the methodology can be found in [2].

The advantage of using undifferenced data is that full advantage of the GPS constellation can be taken, since all satellites tracked at the station contribute to the computation of the synchronization errors and not only the satellites which are tracked (quasi-) simultaneously at the two stations. In addition to this, the single-point positioning concept can give us information about the satellite clocks.

In both approaches, the code and phase data were processed using an elevation cut-off angle of 15°. A 30 s sampling rate was used and station coordinates were fixed to their ITRF97 coordinates. The constant and elevation-dependent antenna phase eccentricity variations were taken into account by using the tables distributed by the IGS. Precise orbits and ERP parameters were made available by the CODE analysis center, which is one of the IGS analysis centers.

RESULTS

INFLUENCE OF THE NEW SETUP

Due to the uncontrolled ambient temperature variations at one of the two sites participating to the tests, we reported previously frequency stabilities varying between 2.10^{-15} and 1.10^{-14} for averaging durations of 4

hours. Now, thanks to the better temperature control, frequency stabilities of 1.5 to 3.10^{-15}, can be obtained on a regular basis, as can be seen from Figure 1.
The first point of the Allan deviations, at τ=30 s,shows the noise of the clock estimates: 10 ps. This noise is comparable to the noise of the single-difference ionospheric-free carrier phase observables.

COMPARISON OF UNDIFFERENCED AND DIFFERENCED METHODS

In Figure 2 we compare the station clock synchronization estimates, obtained from both the undifferenced and the differenced methods. In the undifferenced method, satellite clocks were estimated simultaneously with the clock of Westerbork. The clock of Brussels was chosen as the reference clock. In the differenced method, which is insensitive to satellite clocks, only the differences between the station clocks were estimated. In both cases, a tropospheric zenith path delay was estimated each 15-minute interval. A priori orbit, ERP, and coordinate information was identical in both cases.
Both curves have a very similar behavior and their differences are generally of the order of a few tens of ps, which corresponds to the noise level of single-difference ionospheric-free phase observables.

The difference between the absolute estimates of each day reaches maximally 0.5 ns. Since the absolute value of the synchronization error is obtained from the single-difference ionospheric-free code observables, it is clear that their noise of 2 to 3 ns is one of the limiting factors for the estimation of this offset.

MINIMIZING DISCONTINUITIES AT DAY BOUNDERIES FOR UNDIFFERENCED METHOD

For the single-difference method, we have used overlapping data files to overcome the problem of the day boundary discontinuities. For an overlapping interval of about 8 hours, the rms of the estimated jump varied in our tests between 9-18 ps, which is comparable to the noise level of the observations. The Allan deviation obtained for 5 consecutive days, corrected in this way for the day boundary discontinuities, is shown in Figure 3: 1.10^{-15} for an averaging duration of 32 hours.

CONCLUSION

We have demonstrated that thanks to a better temperature control, frequency transfer between two IGS stations can be routinely performed with a stability of 1.5 to 3.10^{-15} for averaging durations of only 4 hours.

From comparisons between undifferenced and differenced time-transfer methods, we conclude that in our tests the results obtained were equivalent. It is, however, clear that both methods have their distinct advantages and disadvantages.

In the case of the differenced method, we have used overlapping data files to correct for the day boundary discontinuities. For an overlapping interval of 8 hours, the rms of the estimated jumps was of the level of the noise of the single-difference ionospheric-free phase observations. The Allan deviation obtained on a test data set of 5 consecutive days, corrected for the day boundary discontinuities, was 1.10^{-15} for an averaging duration of 32 hours.

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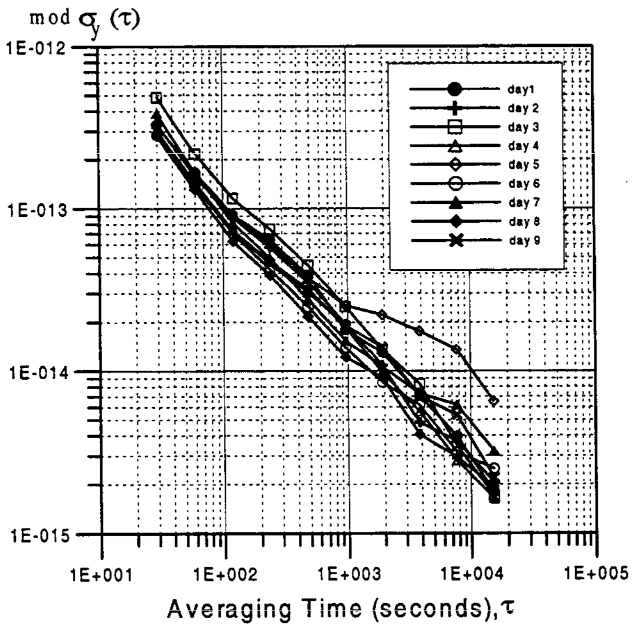

Figure 1 - Modified Allan deviation of the clock estimates computed individually for 9 consecutive days.

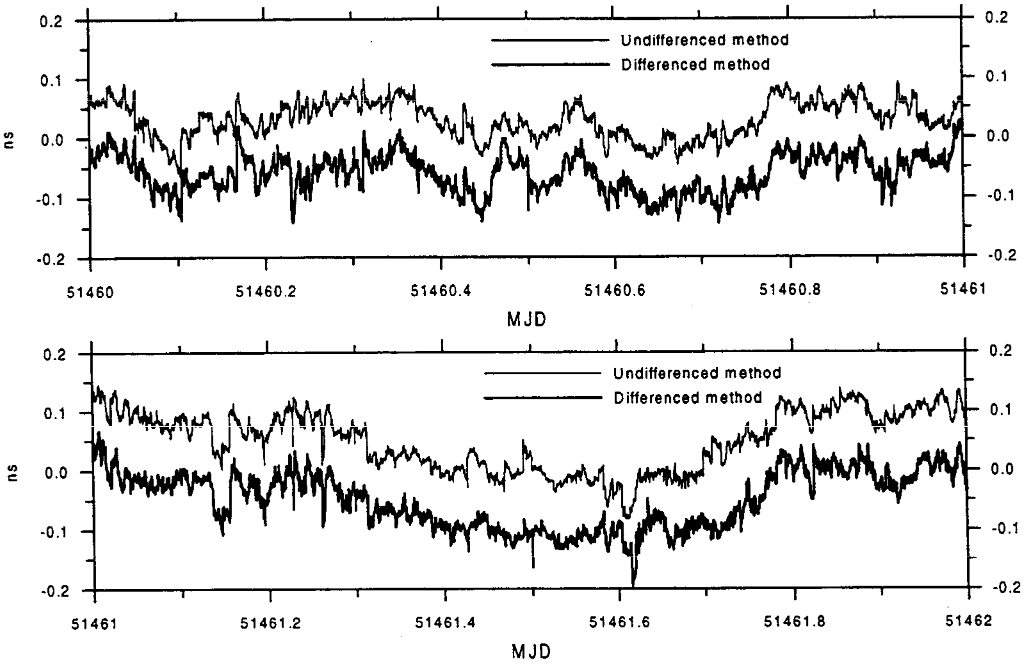

Figure 2 - Comparison of clock estimates obtained from undifferenced and differenced method for two consecutive days. All results have been detrended individually. The curves have been deliberately offset for display purposes.

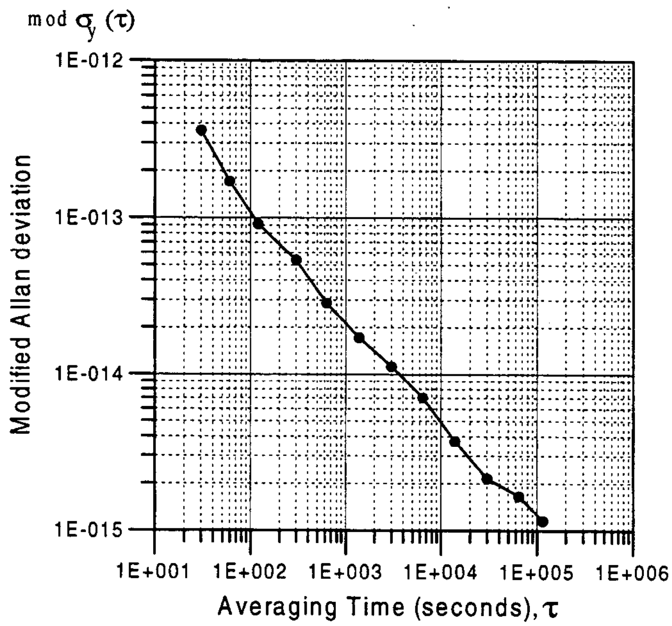

Figure 3 - Modified Allan deviation obtained for the clock estimates for five consecutive days. The discontinuities at the day boundaries have been eliminated by using overlapping data files. The overlap interval was 8 hours.

Questions and Answers

DAVID ALLAN (Allan's Time): Could you put your last MVAR plot up with the results? The first question is: is the slope a -3/2 slope? It looks like it is. Tau to the -3/2. The slope on the data. You can see from the data that it's very close.

CARINE BRUYNINX (Royal Observatory of Belgium): It's between -1 and -2.

ALLAN: Well, you can see from the data that it's very close to -3/2. But the main question I have is that looking at the data visually and looking at the MVAR plot, there is some inconsistency in my mind. I have a question: why don't you see the low frequency part? There should be a flattening in the curve at the bottom due to the low frequency component in the data. And that doesn't seem to show. So I am puzzled.

BRUYNINX: I just ran a program on these data and I got these results. I can try to have a closer look at this because of our recent results.

ALLAN: The technique that Dave Howe suggests using the total variance would allow you to look for longer tau values, and maybe that would clear up the question.

BRUYNINX: Yes, I'm honestly a little bit puzzled by this because, as I told you, I am from the geodetic part and it's my colleague who has been working on these computations about the modified Allan deviations. Maybe you can discuss this with me after this session.

KEN SENIOR (USNO): I was wondering, the slide that you showed indicating the technique you used to deal with the day-boundary discontinuities was due some overlap. That slide, that particular day you looked at, as well as the algorithm, suggests that it's always a constant bias over that time period. And I have looked at several stations and locations and time periods where that's not necessarily true. In fact, I've seen as much as 100-200 picoseconds a day slope difference, which is kind of expected. Because if you have a pseudo-range noise differential between 2 days, the way in which the ambiguities for the phase arcs are being estimated independently might suggest that there would be a slope.

I'm wondering if you've looked at that over many stations, time periods, or do you always see a constant bias?

BRUYNINX: Only this baseline, but we have 2 weeks of data, and I didn't see this slope you were talking about. This is the one you were talking about?

SENIOR: Yes, that's the one.

BRUYNINX: I'm not using any pseudo-range data in this. This is pure carrier phase. The pseudo-range data I used afterwards.

SENIOR: Okay, now I understand, so there were no cycle slips or anything like this?

BRUYNINX: They would break this at the double-difference level.

DAVID HOWE (NIST): If you could put that last slide up again with the modified Allan variance. Not to belabor the issue, but a couple of observations. The actual data look like they could be very optimistic in the long term and just fortuitous that you have somewhat of a semi-sinusoid in that longest term.

The second thing is that there are no confidence limits put on your estimates, and it might be useful to include those.

The third comment is that I would be happy to help you with the total variance approach to see if the onset of flicker is occurring.

BRUYNINX: Thank you. Maybe just one remark. I just got these results last week, so I really intend to have a closer look at everything and try to work on longer time periods, other baselines, and so on. So this is quite preliminary and just out of the computer. But I'll be happy to accept your proposal.